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Chapter 26. Status and Future Directions for Sea Ice Remote Sensing

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26.1 SUMMARY

In Chapter 1 we set out with a rather short list of variables for our marching orders. We identified the need for access to information on the radiation balance, the vertical surface heat and brine fluxes, the horizontal fresh water fluxes, the processes at the ice margins, and the associated ice conditions. We also recognized the need to understand how ice conditions influence operations. We suggested that these needs could be satisfied by data on ice extent and thickness, snow depth, summer melt and melt pond coverage, ice motion and deformation, and the weather and oceanic state. What is our ability to supply this information?

• Ice Extent and Thickness Distribution. The determination of ice extent is the most important capability of microwave observations of sea ice (Chapters 1, 4, 10, 12, 13, 15, 19, and 23), and new ideas are being investigated to enhance this capability (Chapters 25 and 26). Although the rather small areas covered by frazil ice are not observed in some of the microwave data (Chapters 13, 14, and 15), in general the ice extent is well monitored. In view of the dynamic nature of sea ice, the coverage seems adequate in that the resolution of the data is comparable to a day's change in ice edge location. Information on ice thickness is less satisfactory in that it cannot, at present, be measured directly via microwave techniques (Chapter 22). Current research is under way to aid in more accurately resolving the distribution of thin ice types (Chapter 14). One problem is that the thin ice signal in the passive microwave data sets is rendered nearly unusable by the coarse resolution of the observations. New sensor technology will be needed to remedy this. The use of ice type as a thickness proxy, in substitution for the direct resolution of the thicker ice classes, is at best a poor replacement for direct measurement (Chapters 2, 9, 10, 11, and 22). Unfortunately, we doubt that this problem will be resolved in the near future. In the marginal and seasonal ice zones, notably the Greenland and Weddell Seas, there are also numerous unresolved geophysical questions (Chapter 13). Although the quality of the data sets supporting the examination of these regions is improving, because these areas are quite complex and offer significant logistical difficulties for field operations, progress in identifying and monitoring the key surface processes is still limited (Chapters 12 through 15).

• Snow. We cannot presently effectively estimate snow depth on sea ice. There are carefully observed snow signals in the microwave data sets, and there are clear indications, even process models, of microwave sensitivity to the process of snow wetting in warm conditions (Chapters 3, 16, and 17). However, there have been insufficient opportunities for in-situ monitoring of the processes of snow cover formation, metamorphosis, and wetting with good time series of data. Snow thickness and density have great spatial variability, and the large-scale average information that would be useful, say, in thermodynamic ice models, has not been carefully formulated.

• Summer Melt and Pond Formation. The ice processes in summer, including snow melt and pond formation, have also been examined (Chapters 16 and 17), and the stages of snow wetting, snow and ice melt, and pond formation appear to be observable using microwave data. However, these results are tentative because logistical barriers have limited the studies to essentially pilot programs. Current results appear promising for the early melt and early fall, and new data from the first European Remote Sensing Satellite (ERS-1) and the Japanese Earth Resources Satellite (JERS-1) should fill in the midsummer period. Successful

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monitoring of the summer processes is a key to connecting data on sea ice to the current generation of global climate models, and it should have higher priority than it has received to date.

• Ice Motion and Deformation. The motion and deformation of the ice under wind and current stress are measurable in synthetic aperture radar (SAR) data, and in visible and infrared images such as those taken by the Advanced Very High-Resolution Radiometer (AVHRR). Given fine-scale ice motion data, other terms such as the estimation of freshwater fluxes due to ice melting can be made. Motion is sometimes difficult to determine in areas of high deformation, in areas of new ice, and perhaps in summer, but, in general, current capabilities for determining ice motion appear to be quite robust (Chapter 18). During the operational period for the Radar Satellite (Radarsat) (1995–2000), SAR coverage will be adequate for those needs. Finally, we need to test the geophysical validity of the ice motion data sets by determining whether the time series of the fine-scale ice motion field and estimates of thermodynamic flux fields will together yield an accurate thickness distribution, as they should.

• Weather and Oceanic State. A major gap exists with the absence of routine, high-quality information on the characteristics of the atmospheric and oceanic boundary layers in contact with the ice. The quality of the analyses for the weather over ice-covered seas is improving, but the accuracy of these analyses, in particular for the Southern Ocean, remains largely untested. Fortunately, ocean data sets are available from an expanding array of drifters and moorings, but these measurements cannot adequately monitor the seas, especially the ice-covered seas. For climatological studies, the lack of upper ocean data may prove to be very limiting.

26.2 FUTURE DIRECTIONS

It is clear that we require additional information on the microwave and physical properties of the ice, and additional development of algorithms for generating sea-ice geophysical data products, before we can adequately interpret satellite observations. This information is coming by way of in-situ observations, laboratory investigations, and theoretical modeling, with good progress noted in all these areas. Continued work in field, laboratory, and theoretical regimes is critically needed, especially on a better understanding of the processes of the summer season, the determination of snow cover properties, and the nature of the thin and thick ice species.

Sea ice investigators have, in the past, obtained useful in-situ data on various ice conditions by participating in field studies whose primary focus was not on remote-sensing technology development and testing; the microwave investigators have piggybacked on other programs. It is likely that this approach has inherent value and will continue. In fact, in areas of broad interest, such as the zones of oceanic convection, such deployments are in place now with more planned for the future. However, studies leading to microwave signature development and algorithm validation necessitate improved experimental designs. A better record and a more thorough understanding of the evolution of active and passive signatures throughout the year and at a variety of sites are needed.

The scales of variation originate variously in the ocean, the ice itself, the atmosphere, and the snow cover; together they range from submillimeter brine inclusions to storms covering thousands of kilometers, and they challenge our interpretations and confound our validation efforts. These variations are not only "noise" in a determination of a mean field, they are also the signals of processes. We have learned something about these variations, but there is much left to do in understanding them, in terms of both geophysics and algorithms accuracy.

Some clearly powerful applications are in their infancy. The use of the Kalman smoother (Chapter 24) is a prime example. With it, we can combine data sets with physical models that simulate the temporal behavior as aspects of the geophysical system; without some data assimilation techniques, we must treat each observation as an isolated event. Another research area with strong potential, not discussed in this book since adequate data are only now being collected, is the merging of active and passive microwave data sets. Given some necessary information about the microwave behavior of the thin ice species, the combination of the derived ice motion with the observed microwave radiance will make it possible to move beyond the use of simple, instantaneous ice concentration, a troublesome variable in the rapidly changing ice-covered seas. Other analyses involving the merging of data sets, including infrared and visible-light radiances, will surely evolve; the infrared data utilization is especially desirable in that infrared data can provide sea and ice surface temperatures [Key and Haefliger, 1992].

In the development of algorithms for generating geophysical data sets, there are areas, such as fluxes in polynyas, where good results have already been obtained, and there is promise in a number of additional areas, such as the evolution of thin ice and snow cover. However, a problem permeates all sea ice algorithm development—direct validation is essential, but has not as yet been accomplished. As a result, we have been forced to resort to unsatisfactory comparisons. In Chapter 11, validations consisting of two or more microwave data sets or a microwave and satellite visible (or infrared) image are discussed, and in neither case can ice type or concentration be properly validated. In the area of validation, we need the assistance of the traditional glaciological and oceanographic communities in generating data sets for comparison purposes. The sampling issue arising from comparisons of areal information and point observations must be examined. We can generate data sets that are purely measures of change in microwave properties, but they will not provide scientifically acceptable climate-change information until their relation to traditional geophysical variables is fully demonstrated.

exploit the new multispectral data to be acquired by the Earth Observing System (EOS) sensors.

26.5 CONCLUSION

In applying remote sensing methods to observing sea ice for either research or operational purposes, one is faced with a reasonably clear-cut set of requirements and supplied with steadily improving data sets. While sea ice would indeed seem to be a reasonably simple and well-behaved material to monitor, it has proven to be far from simple in its microwave properties; the complexity of these properties is the theme throughout this book. The successful interplay of experimental and theoretical work is only just now maturing (e.g., in the examination of thin ice evolution), and this collaboration is essential to good progress. The analysis of satellite data has progressed well; there is much that we know how to do with this excellent data set, and significant augmentations of the archived sea ice data set will continue in the future. At the same time there are issues still to explore and many algorithms to develop, as we cannot yet determine many of the key state variables of the polar seas, nor can we properly validate much of our derived information. To address some variables, notably ice thickness, we clearly need additional data sets, such as the sonar ice-draft data. For new information on thin ice, summer processes, ice margin processes, and snow cover, we need continued theoretical progress, field and laboratory programs, and new data sets from improved sensors, such as the polarimetric SAR and the finer resolution microwave radiometers now in design. Work on improving our description of ice is proceeding with enthusiasm at a number of institutions, and highly interesting results have been presented at meetings in the brief period since these chapters were written. At this time, air–sea–ice interaction research is needed in the form of the generation and interpretation of accurate geophysical data sets that characterize those interactions within the global climate. This book has been written to assist that activity.

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26.3 SEA ICE IN THE CONTEXT OF GLOBAL CHANGE

An examination of the role of ice in the climate system, and the form that its investigation should take, is of considerable significance in any appraisal of current capabilities for monitoring the properties and processes of the ice cover.

There is currently considerable uncertainty in the resilience of sea ice cover to global warming conditions. Projections by global climate models of polar climate response to greenhouse gas-induced warming indicate the well-known increase in winter temperatures in high latitudes. The models suggest that warming may exceed 10°C for a CO_2 equivalent doubling as a result of the stability of the lower troposphere in high latitudes [Houghton et al., 1990]. In the transition seasons, the response is enhanced by the modeled temperature snow–ice albedo positive feedback. In the summer, however, the projected high latitude warming is less than the global average. Most model experiments show a substantial retreat and thinning of sea ice [Meehl and Washington, 1990], with some suggesting almost ice-free summers in the Arctic and Antarctic Oceans. However, a survey of 17 different climate models indicates that the simulated feedback of temperature snow–ice albedo effects ranges from weakly negative to strongly positive as a result of the complex interactions of shortwave and infrared radiation with snow–ice surfaces and cloud cover [Cess et al., 1991]. A further area of model shortcomings is in the treatment of snow on ice and leads. Given these uncertainties, additional data on the variability of sea ice extent, concentration, and thickness can assist in improving the parameterizations and validation of sea ice and coupled climate models [European Space Agency, 1985; Ledley, 1988; Morassutti, 1991].

Until now, only a limited quantity of ice thickness data has been available. Under-ice draft measurements have been obtained by upward-looking sonar on operational submarines and, more recently, by moored sensors. Changes have been reported in mean ice draft and open water coverage where submarine observations have been collected in the same area in different years [Wadhams, 1992]. However, even where the measurements were taken at the same season and along an identical transect, lack of knowledge of the inherent interyear variability precludes the accurate estimation of a trend. Monitoring of ice draft distribution by moored upward-looking sonars and by remotely controlled unmanned underwater vehicles is expected to provide answers to this question over the next decade. The application of accurate satellite ice algorithms incorporating improved weather filters and thin ice determinations should make significant contributions to this work.

Another prediction of the CO_2 doubling experiments is a general increase in precipitation in high latitudes, associated with increased open water and increased atmospheric vapor content. Since temperatures in winter will remain well below freezing, this may give rise to increased snowfall, as has been observed in southwestern Alaska during warm winters [Mayo and March, 1990]. Thicker snow cover may have the effect of decreasing the growth of land-fast ice, as noted at Alert, Northwest Territories in the 1970's–1980's [Brown, R. D. and P. Cole, Interannual variability of land-fast ice thickness in the Canadian High Arctic, 1950–1989, submitted to *Arctic*, 1992]. Conversely, Brown and Cole found a trend of thickening ice at Resolute associated with several years of decreased snow cover. Such local weather-induced complications show the necessity for a basin-wide analysis of changes in ice thickness, open water production, and snow properties.

26.4 APPLICATIONS OF SATELLITE DATA PRODUCTS

The availability of daily passive-microwave-derived ice extent and concentration data offers important opportunities for improving global weather analyses and forecasts. The provision of accurate all-weather maps of sea ice limits and concentrations within the pack ice is of direct importance for the operation of ships navigating in or near the ice [Brigham, 1991]. However, as operational weather forecasting models are upgraded to incorporate more elaborate parameterizations of surface processes, it will be necessary to incorporate the effects of turbulent fluxes of sensible and latent heat from polynyas and open leads on the atmospheric boundary layer. Data on ice concentration and roughness can also improve determinations of aerodynamic roughness lengths in the marginal ice zone and over the central pack.

The products derived from the Scanning Multichannel Microwave Radiometer and the Special Sensor Microwave/Imager are already widely distributed by the National Snow and Ice Data Center [Barry, 1991]. To these will be added the geophysical products from the Alaska SAR facility [Weeks et al., 1991]. These data sets are widely used for both analyses of ice–climate interactions [Cavalieri and Parkinson, 1981; Barry and Maslanik, 1989; Zwally and Walsh, 1987] and ice–ocean interactions [Jacobs and Comiso, 1989] to examine trends in ice extent and concentration [Parkinson and Cavalieri, 1989; Gloersen and Campbell, 1991] and to improve algorithm development [Comiso and Sullivan, 1985; Maslanik, 1992; Walters et al., 1987]. Ready availability and wide dissemination of such data sets are certain to enhance our knowledge and understanding of polar sea ice and its role in the climate system.

By the year 2000, there will be a nearly continuous record of global sea ice extent spanning more than 25 years and a time series of ice concentration data for almost that long. This will enable more definite assessments to be made concerning decadal-scale trends in ice area and should permit short-term variability and its regional expression to be defined more reliably. Eight years of SAR data will be available, which will provide a detailed look at the mechanistic interactions within the ice pack. The nature of atmospheric forcings on ice motion and the seasonal cycles of ice growth and decay will be clearer and their modeling with coupled atmosphere–ocean–ice models should be well in hand. The research community will thus be fully equipped with the knowledge and technical tools necessary to fully